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Dynamic Security Assessment

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15.1 Definitions and Historical Perspective

Power system security in the context of this chapter is concerned with the technical performance and quality of service when a disturbance causes a change in system conditions. Strictly speaking, every small change in load is a disturbance that causes a change in system conditions; however, this topic focuses on what could be called “large changes” in system conditions. These changes are referred to as “contingencies.” Most commonly, contingencies result in relay operations that are designed to protect the system from faults or abnormal conditions. Typical relay operations result in the loss of a line, transformer, generator, or major load.

When changes occur, the various components of the power system respond and hopefully reach a new equilibrium condition that is acceptable according to some criteria. Mathematical analysis of these responses and new equilibrium condition is called security analysis. If the analysis evaluates only the expected postdisturbance equilibrium condition (steady-state operating point), this is called static security assessment (SSA). If the analysis evaluates the transient performance of the system as it progresses after the disturbance, this is called dynamic security assessment (DSA). DSA has been formally defined by the Institute of Electrical and Electronics Engineers (IEEE), Power Engineering Society’s (PES), working group on DSA as

Dynamic Security Assessment is an evaluation of the ability of a certain power system to withstand a defined set of contingencies and to survive the transition to an acceptable steady-state condition.

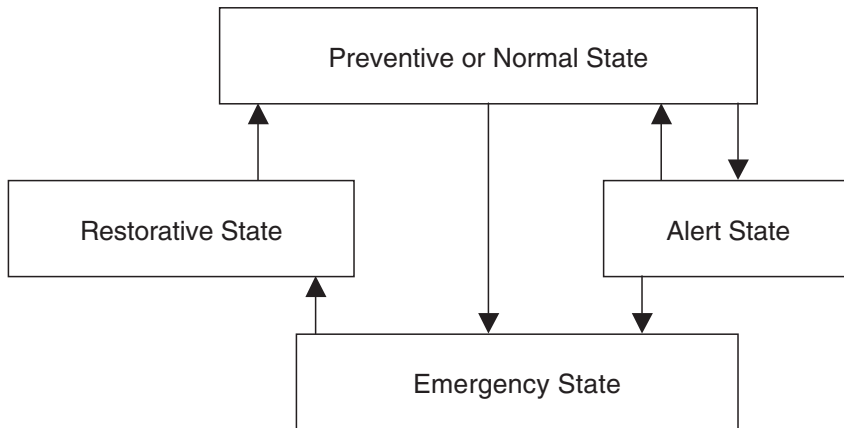


FIGURE 15.1 Operating states.

Very early power systems were often separate and isolated regions of generators and loads. As systems became larger and more interconnected, the possibility of disturbances propagating long distances increased. The Northeast blackout of November 1965 started a major emphasis on the reliability and security of electric power systems. The benchmark paper by Tom Dy Liacco introduced the concept of the preventive (normal), emergency, and restorative operating states and their associated controls (Dy Liacco, 1967). The preventive state is the normal state wherein the system is stable with all components within operating constraints. The emergency state arises when the system begins to lose stability, or when component operating constraints are violated. The restorative state is when service to some customers has been lost—usually due to progression through the emergency state and the operation of protective devices. A significant extension added the alert state between the preventative (or normal) state and the emergency state as shown in Fig. 15.1 (Cihlar et al., 1969).

This is a significant extension because it introduced the concept of a “potential emergency.” If the occurrence of a likely contingency causes instability or operation with constraint violations, the system is said to be in the alert state and classified as “insecure.” An extensive report of DSA practices in North America in the late 1980s summarized the status of DSA as it had emerged up to that time (Fouad, 1988).

15.2 Criteria for Security

In terms of operating states, a system is said to be secure if it is in the normal state and will remain in the normal state following any single likely contingency. If a system is in the normal state but will not remain in the normal state following any single likely contingency, then it is reclassified into the alert state and considered insecure. The first key criterion here is the concept of “remain in the normal state.” SSA can be used to quickly determine if the system is insecure by simply looking at the static outcome of each contingency. However, to be fully secure, DSA must be used to determine if the associated dynamics of each contingency are acceptable. For example, while the voltage levels of the postcontingency system may be normal (as determined by SSA), it is possible that the transient voltage dips during the disturbance may be unacceptable. Furthermore, SSA cannot easily determine if the postcontingency system is stable, or can even be reached due to the transients of the contingency.

The second key criterion is the definition of “likely contingency.” The list of likely contingencies varies from control area to control area, depending on operating practice. In most cases, the list consists of single outages such as the loss of a line, transformer, or generator. This is called the “ $N - 1$ ” security criterion—where N refers to the total number of possible elements that could be outaged. In other cases, the list may include more complex contingencies that are known to occur with some frequency, and may include a sequence of events such as a fault on for a specified time followed by relay clearing.

15.3 Assessment and Control

The adoption of security concepts for electric power systems clearly separates the two functions of assessment and control. Assessment is the analysis necessary to determine the outcome of a “likely” contingency (possibly including all existing automatic controls). Control is the operator intervention or automatic action that might be designed for use to avoid the contingency entirely, or to remedy unacceptable postcontingency conditions. When the controls are implemented, they may then become a part of the assessment analysis through a modification of the contingency description.

Preventative control is the action taken to maneuver the system from the alert state back to the normal state. This type of control may be slow, and may be guided by extensive analysis. Emergency control is the action taken when the system has already entered the emergency state. This type of control must be fast and guided by predefined automatic remedial schemes. Restorative control is the action taken to return the system from the restorative state to the normal state. This type of control may be slow, and may be guided by analysis and predefined remedial schemes.

15.4 Dynamic Phenomena of Interest

While there are numerous phenomena that are of interest in dynamic analysis, typical DSA programs focus primarily on two phenomena—voltage transients and system stability. The voltage transients are important because they must remain within acceptable limits to avoid further damage or loss of equipment. Normally the effects of under/over voltage transients are not included in the large-scale programs that are used for DSA. That is, the automatic tripping and relaying associated with under/over voltage are not normally modeled as part of the simulation that is being used for DSA. Since these possible actions are not explicitly modeled, the programs simply monitor voltage levels as they progress during a transient.

One of the most basic concepts of system stability is the issue of maintaining synchronous operation of the AC generators. This is usually referred to as “transient stability,” and is discussed later in this chapter. Current DSA programs focus primarily on this type of stability and its associated constraint on operations.

As generator electromechanical dynamics progress during a disturbance, the system voltages and currents can change markedly. These changes can impact voltage-sensitive loads and result in conditions that may be unacceptable even though the generators remain in synchronism. In severe cases, voltage levels can reach points where recovery to nominal levels is impossible. Such voltage collapse conditions normally result in further deterioration of the system and additional relay action or loss of synchronism (Taylor, 1994). The extent to which such phenomena can be detected in DSA programs depends on the level of modeling detail for control systems, relays, and loads.

15.5 Timescales

Power system dynamics include a very wide timescale classification (Sauer and Pai, 1998). These can be loosely described by six categories as shown in Table 15.1.

In order to analyze this wide range of timescale behavior, considerable care must be given both to efficient modeling and numerical techniques. The majority of current DSA programs consider the

TABLE 15.1 Power System Timescales

Lightning propagation	Microseconds to milliseconds
Switching surges	Microseconds to tenths of seconds
Electrical transients	Milliseconds to seconds
Electromechanical	Hundredths of seconds to tens of seconds
Mechanical	Tenths of seconds to hundreds of seconds
Thermal	Seconds to thousands of seconds

dynamics ranging from hundredths of seconds to tens of seconds (the electromechanical dynamics). The challenge of modeling this time range includes properly including the effects of the faster phenomena without explicitly including their fast transients.

15.6 Transient Stability

In alternating current (AC) systems, the generators must all operate in synchronism in steady state. When a fault occurs on the system, the electrical power output of some generators (usually those near the fault) will tend to decrease. Since the turbine power input does not change instantaneously to match this, these generators will accelerate above the nominal synchronous speed. At the same time, the electrical power output of other generators may increase, resulting in deceleration below the nominal synchronous speed. As a fundamental property of rotating equipment, the generators must all reverse their trends before the energy imbalances become so large that return to synchronous operation is impossible. Transient stability analysis focuses on this phenomenon, which can be visualized through a ball resting in a potential energy well as shown in Fig. 15.2a. In steady state, the ball is at rest (signifying all generators in synchronism) in the well bottom. Clearly any small, temporary displacement of the ball will result in a return to the “stable” well bottom. However, if the disturbance is large enough that the ball is pushed over the well boundary, it will not return to the same well bottom. While it may come to rest at some other point, transient stability analysis is concerned with the detection of when the ball will leave the initial well boundary. That is, a fault will cause the ball to move up the side of the well, and must be cleared soon enough in time that the ball never leaves the well (Fig. 15.2b). When the fault remains on the system for too long, the ball picks up sufficient kinetic energy to carry it over the well boundary (Fig. 15.2c).

When generators accelerate or decelerate with respect to each other, their speed deviations (and corresponding angle deviations) constitute swings. If two or more generators swing apart in speed and then reverse, their return to synchronism could be considered “first-swing stable,” if the analysis concludes at the point of return. In many cases, this is sufficient to ensure that the system will remain in synchronism for all time after the return. However, in other cases, the system dynamics may be such that the loss of synchronism does not occur until generators have experienced multiple swings. Deciding when to stop a simulation and declare the result either stable or unstable remains a challenge in DSA analysis.

15.7 Modeling

In order to perform computer simulation of the dynamics that may arise during and after a contingency, it is necessary to formulate mathematical equations that capture the fundamental transients. For the phenomena and timescales of interest in current DSA, ordinary differential equations are considered sufficient. Since the primary dynamics of interest are the electromechanical transients (shaft speeds), there will be two differential equations for each generator modeled. In addition, there may be many

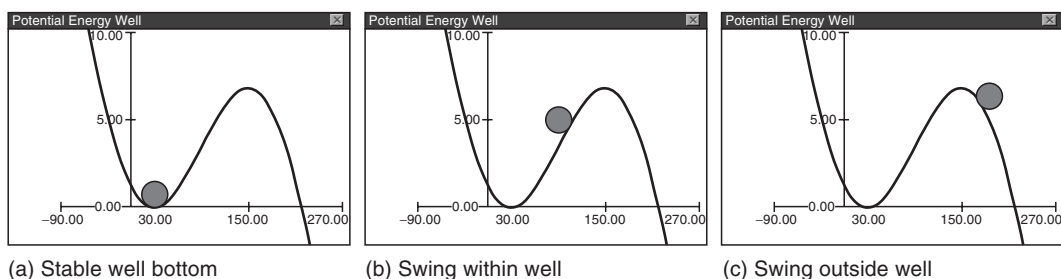


FIGURE 15.2 Transient stability and the energy well.

associated dynamics and controls that influence the electromechanical transients. Finally, there are the quasisteady-state approximations of the remaining faster and slower dynamics that enter the model as algebraic equations. The resulting mathematical model has the form given in the following equations:

$$\frac{d\delta}{dt} = \omega - \omega_s \quad (15.1)$$

$$\frac{d\omega}{dt} = f(\omega, x, y) \quad (15.2)$$

$$\frac{dx}{dt} = g(\omega, x, y) \quad (15.3)$$

$$0 = h(\delta, x, y) \quad (15.4)$$

In addition, the algebraic equations may need to be modified during simulation to reflect the changes that occur in the network topology as time progresses between a fault application and subsequent clearing. Since it is difficult to guarantee the existence of a “ y ” solution for the algebraic equations as the dynamic states evolve, this combination of differential and algebraic equations poses theoretical as well as numerical challenges for DSA. Details of the composition of these mathematical models are given in references (Anderson and Fouad, 1993; Kundur, 1994; Sauer and Pai, 1998). Additional issues are often important in DSA analysis as discussed in the following section.

15.8 Criteria and Methods

In practice, the typical criteria for DSA include (IEEE, 1998):

Inertial stability criteria. This mainly concerns the evolution of relative machine angles and frequencies.

Voltage excursions (dip or rise) beyond specified threshold level and duration. These include separate voltage excursion threshold/duration pairs for voltage dip and voltage rise, and maximum/minimum instantaneous excursion thresholds.

Relay margin criteria. These are defined for predisturbance and postdisturbance conditions. If relay margin is violated for more than a maximum specified time after the disturbance, it is identified as insecure.

Minimum damping criteria. For a designated list of contingencies, if the postdisturbance system exhibits oscillations, they must be positively damped (decreasing in amplitude).

Identifying the specific set of security constraints to be introduced for the dynamic security studies is based on experience, knowledge of the system, and judgment of the planning and operations engineers. Generally, the objective of DSA is to determine the contingencies that may cause power system limit violations or system instability. The ultimate goal is to generate the operating guidelines for defining the areas of secure operation. Generating the operating guidelines includes selecting contingencies, performing a detailed stability study, and analyzing the results for violations. Proposed methods for DSA can be divided into three areas: simulation (numerical integration method, direct or Lyapunov methods, and probabilistic), heuristic (expert system), and database or pattern matching approaches. An overview of these methods is provided below.

15.8.1 Numerical Integration

The numerical integration algorithms are used to solve the set of first-order differential equations that describe the dynamics of a system model (Dommel and Sato, 1972). Numerical integration provides solutions relating to the stability of the system depending on the detail of the models employed. This is the most widely applied approach in off-line environments, but is generally too computationally intensive for on-line application.

15.8.2 Direct/Lyapunov Methods (See also Chapter 11)

This approach is also referred to as the transient energy function (TEF) methods. The idea is to replace the numerical integration by stability criteria. The value of a suitably designed Lyapunov function V is calculated at the instant of the last switching in the system and compared to a previously determined critical value V_{cr} . If V is smaller than V_{cr} , the postfault transient process is stable (Ribbens-Pavella and Evans, 1985). In practice, there are still some unresolved problems and drawbacks of this approach. The efficiency of this method depends on simplification of the system variables. The integration of the fault on system equations is needed to obtain the critical value for assessing stability. It is difficult to construct the appropriate Lyapunov function to reflect the internal characteristics of the system. The method is rigorous only when the operating point is within the estimated stability region.

15.8.3 Probabilistic Methods (Anderson and Bose, 1983)

With these methods, stability analysis is viewed as a probabilistic rather than a deterministic problem because the disturbance factors (type and location of the fault) and the condition of the system (loading and configuration) are probabilistic in nature. Therefore, this method attempts to determine the probability distributions for power system stability. It assesses the probability that the system remains stable should the specified disturbance occur. A large number of faults are considered at different locations and with different clearing schemes. In order to have statistically meaningful results, a large amount of computation time is required (Patton, 1974). Therefore, this method is more appropriate for planning. Combined with pattern recognition techniques, it may be of value for on-line application.

15.8.4 Expert System Methods

In this approach, the expert knowledge is encoded in a rule-based program. An expert system is composed of two parts: a knowledge base and a set of inference rules. Typically, the expertise for the knowledge base is derived from operators with extensive experience on a particular system. Still, information obtained off-line from stability analyses could be used to supplement this knowledge. The primary advantage of this approach is that it reflects the actual operation of power systems, which is largely heuristic based on experience. The obvious drawback is that it has become increasingly difficult to understand the limits of systems under today's market conditions characterized by historically high numbers of transactions.

15.8.5 Database or Pattern Recognition Methods

The goal of these methods is to establish a functional relationship between the selected features and the location of system state relative to the boundary of the region of stability (Patton, 1974; Hakim, 1992; Wehenkel, 1998). This method uses two stages to classify the system security: (a) feature extraction and (b) classification. The first stage includes off-line generation of a training set of stable and unstable operation states and a space transformation process that reduces the high dimensionality of the initial system description. The second stage is the determination of the classifier function (decision rule) using a training set of labeled patterns. This function is used to classify the actual operating state for a given contingency. Typically, the classifier part of this approach is implemented using artificial neural networks (ANNs).

15.9 Recent Activity

In recent years, there have been several database or pattern matching methods introduced for finding security limits (El-Keib and Ma, 1995; Chauhan and Dava, 1997; Chen et al., 2000). The essential idea is to select a set of representative features (such as line flows, loads, and generator limits) and then train an

estimator (typically an ANN) on simulation data in order to estimate the security margin. The estimator is expected to interpolate or generalize to similar unstudied cases. For on-line application, a pattern matching or interpolation method rather than analytic approaches may be most appropriate. Among the alternative methods, ANNs seems very promising (Sobajic and Pao, 1989; Pao and Sobajic, 1992; Mansour et al., 1997) because they have excellent generalization capabilities, superior noise rejection, and fast execution (with most of the calculations occurring during the initial off-line training).

A recent report with survey results (Sauer et al., 2004) quite clearly showed that there is a major gap in the operations security tools. This gap is the lack of an ability to evaluate stability margins in real time. This report also included results from a project that focused on this gap and investigated the feasibility of a new technique for bringing dynamic analysis into the operations environment. The work started with two of the most time-consuming aspects of stability margin analysis: time-domain simulation and static voltage margin computations. In a previous Power System Engineering Research Center (PSERC) project (Tomsovic et al., 2003), it was shown that a system of estimators based on neural networks could accurately and quickly estimate security margins for on-line application. This project produced a number of contributions to the development of dynamic security analysis techniques.

- A comprehensive framework was developed for on-line estimation of security margins, calculated based on current operating practices.
- The framework proposed families of estimators, each specialized for specific system limits and the appropriate security criteria (i.e., static, dynamic, or voltage). The estimators can be combined to provide an overall assessment of system operating conditions.
- A system of estimators was implemented and tested on a modified New England 39 bus system.
- On the basis of the insights from the New England system, a more sophisticated set of estimators were implemented and tested on a 6000 bus model of the Western area system. The focus of this study was the California–Oregon Intertie transfer limits.
- A number of software tools were developed to help automate the process of evaluating security margins in off-line studies.
- The results show that it is possible to very accurately estimate security margins for large systems on-line. The main limitation of the approach resides in the ability of time-consuming off-line studies to accurately model system dynamics.

15.10 Off-Line DSA

In off-line DSA analysis, detailed time-domain stability analysis is performed for all credible contingencies and a variety of operating conditions. In most cases, this off-line analysis is used to determine limits of power transfers across important system interfaces. These limits then are used in an operating environment that is hopefully not significantly different from those conditions considered. Since the analysis is performed off-line, there is not a severe restriction on computation time and therefore detailed analysis can be done for a wide range of conditions and contingencies. These studies include numerical integration of the models discussed above for a certain proposed power transfer condition and for a list of contingencies typically defined by a faulted location and specified fault-clearing time (based on known relay settings).

The trajectories of the simulation are analyzed to see if voltage transients are acceptable, and to see if transient stability is maintained for the specified fault-clearing time. If the results for one level of power transfer are acceptable for all credible contingencies, the level of proposed power transfer is increased and the analysis is repeated. This process continues until the level of power transfer reaches a point where the system cannot survive all of the credible contingencies. The maximum allowable transfer level is then fixed at the last acceptable level, or reduced by some small amount to provide a margin that would account for changes in conditions when the actual limit is in force.

15.11 On-Line DSA

On-line DSA is used to supplement (or update) off-line DSA to consider current operating conditions. A basic on-line DSA framework includes essentially two steps. The first involves a rapid screening process to limit the number of contingencies that must be evaluated in detail. This rapid screening process might consist of some direct method that avoids long numerical integration times (Pai, 1989; Fouad and Vittal, 1992; Pavella and Murthy, 1993; Chadalavada et al., 1997). In addition to giving fast stability evaluation, these methods inherently include a mechanism for assessing the severity of a contingency. That is, if a system is determined to be stable, the direct methods also provide an indication of “how stable” the system is. This indication usually takes the form of an “energy margin.” For example, in reference to the ball motion of Fig. 15.2, the maximum swing of the ball up the side of the energy well could be used to quantify how “close” the ball was to leaving the well.

Most of these methods still require some numerical integration to simulate the impact of a major disturbance and then predict stability or compute a margin to instability. Computation of the margin usually requires the simulation to force the system into an instability, perhaps either by using a sustained fault, or reapplication of the fault after scheduled clearing (Vaahedi et al., 1996).

This first step includes a decision process of which contingencies must be studied in greater detail. Those that are judged to be “sufficiently stable” need not be studied further. Those that are considered “marginal” must be studied further. This process includes a ranking strategy that is usually based on the energy margin computed in the direct method. Additional criteria involving artificial intelligence approaches can also be used to aid the decision process (El-Kady et al., 1990).

The second step involves traditional time-domain simulation that includes extensive numerical integration to reveal swing trajectories and voltage variations. This is performed on a small subset of contingencies that were judged to be marginal according to the screening process of step one.

In on-line studies, the time for computation is a severe constraint in addition to the challenge of interpretation and quantification of results. Typical performance goals for on-line DSA program are to process 30 contingencies (each having 10 s of simulated time) for a 2000 bus, 250 generator system in 10 min (Ejebe, 1998).

15.12 Status and Summary

A recent survey of existing DSA tools provides a detailed description of the status of DSA tools (Vittal et al., 2005). With the increase in transactions on the bulk power system there is a critical need to determine transient security in an on-line setting and also perform preventive or corrective control if the analysis indicates that the system is insecure. In recent years, the industry has seen the development of large generation projects at concentrated areas of available fuel supplies. The stability properties of the system have been drastically altered, while the new “nonutility” plants are not cognizant of their impact on system stability. In this environment, stability issues may and will affect available transfer capability. Stability problems may not happen frequently, but their impact, when they do happen, can be enormous. Most of the time, off-line studies are performed to determine conservative limits. In the new environment, the responsibility of monitoring system stability may be vested with the regional transmission organization (RTO) and on-line stability monitoring may be necessary.

This section deals with reviewing the current state-of-the-art in the area of on-line transient stability assessment, evaluating promising new technologies, and identifying technical and computational requirements for calculating transient stability limits and corrective and preventive control strategies for cases that are transiently insecure.

Six on-line transient stability package vendors were identified by conducting a literature survey. A detailed questionnaire that addressed several pertinent issues relating to on-line transient stability assessment was prepared. All six vendors responded to the questionnaire. The responses received were

carefully analyzed. This analysis provided a detailed overview of the capabilities of available tools, performance metrics, modeling features, and protective and corrective control measures.

An elaborate questionnaire was then prepared and sent to all PSERC member companies. This questionnaire addressed specific needs in terms of required features, preferred performance, and control capabilities. A detailed analysis of the received responses provided a clear picture of the desired features and performance specifications of an on-line transient stability assessment tool.

A comparison of the analysis conducted on the vendor responses and the PSERC member company responses identified areas and topics that needed further development and research. This information will be useful in soliciting new research proposals and providing vendors a guide to the features that need to be developed and implemented.

A literature survey was also conducted on new analytical developments in on-line transient stability analysis. On the basis of this review, novel concepts based on quadratized models for power system components were explored to investigate whether there would be a significant advantage gained in using these models in terms of accuracy and computational burden.

DSA is concerned with the ability of an electric power system to survive a major disturbance. It must assess the quality of the transient behavior as well as stability. DSA is performed both in off-line and on-line environments and is computationally intensive due to the numerical integration involved in evaluating the transient behavior of the system during major disturbances. Several recent and ongoing projects have addressed the computational issue through screening techniques that provide rapid analysis of stability outcomes and stability margins (Demaree et al., 1994; Meyer et al., 1997). Research in this area is continuing as the need for DSA to evaluate available transfer capability (ATC) becomes stronger in the restructured industry.

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